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ASCA Observations of Soft X-Ray Transients in Quiescence : X1608−52 and Cen X-4

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Abstract

We observed soft X-ray transients, X1608−52 and Cen X-4, in quiescence with ASCA at X-ray luminosities on the order of 10^{32-33} erg s^{-1} . The energy spectra were rather soft for both sources. Blackbody fits to the data required characteristic temperatures of 0.2–0.3 keV and emission regions of ~ 10 km^2. A conspicuous hard tail remained after fitting Cen X-4 with a blackbody curve. An extremely soft spectrum in quiescence seems to be a common property of soft X-ray transients.

Key words: Stars: neutron — X-rays: binaries — X-rays: sources — X-rays: transients

1. Introduction

Transient X-ray sources can be classified into three groups: hard transients, soft transients, and ultra-soft transients (Cominsky et al. 1978; Kaluzienski et al. 1977; Kitamoto et al. 1990). The hard transients are generally X-ray pulsars orbiting around Be stars. The soft transients are low-mass X-ray binaries (LMXBs) containing neutron stars, since Type-I X-ray bursts are often detected in these systems. The ultra-soft transients are believed to contain black holes. The mechanism of the transient phenomenon in the soft and ultra-soft transients has yet to be understood well. Two competing instability models have been suggested: an accretion-disk instability (Taam, Lin 1984; Cannizzo et al. 1985) and a mass-overflow instability on the companion-star surface (Osaki 1985; Hameury et al. 1986). Mineshige et al. (1992) have argued that the low X-ray luminosity of GS 2000+25, observed with Ginga, would be insufficient to trigger a mass-overflow instability on the surface region of the companion star.

Recently, Verbunt et al. (1994) reported the results of ROSAT observations of the soft X-ray transient Aql X-1 at X-ray luminosities varying from $\sim 4 \times 10^{32}$ erg s^{-1} to $\sim 2 \times 10^{36}$ erg s^{-1} in 0.4–2.4 keV for an assumed distance of 2.5 kpc. The characteristic temperature determined by blackbody fits varied from ~ 0.31 keV to ~ 0.55 keV as the luminosity increased from $\sim 4 \times 10^{32}$ erg s^{-1} to $\sim 2 \times 10^{36}$ erg s^{-1}. The authors consider that the emission area of ~ 1 km^2 in quiescence is due to funneling of the accreting matter by a magnetic field, or to dominant emission from a boundary layer formed between the accretion disk and the neutron-star surface.

Wagner et al. (1994) detected a black hole candidate, X-ray nova GS 2023+338 (V404 Cyg), with ROSAT 1265 days after outburst. The luminosity was 8×10^{33} erg s^{-1} and the spectrum was very soft: $kT = 0.21$ keV, if it is approximated as being a blackbody.

X1608−52 has been classified as a soft X-ray transient due to large luminosity variations of a few orders of magnitude on time scales of a few hundred days (Bradt, McClintock 1983; Lochner, Roussel-Dupré 1994). X1608−52 was observed with Tenma in 1983 and 1984 at an X-ray luminosity continuously varying from $L_{\rm x} \sim 3 \times 10^{37}$ erg s^{-1} to $\sim 3 \times 10^{36}$ erg s^{-1} (with an assumed distance of 3.6 kpc; see below). The spectrum showed a transition from thermal to power law when the luminosity decreased below $\sim 10^{37}$ erg s^{-1} (Mitsuda et al. 1989). In observations with Ginga in 1989, 1990, and 1991, the luminosities were on the order of 10^{36} erg s^{-1} (Yoshida et al. 1993), during which periods the spectrum was a power law. It was shown that the change from ther-

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mal to power law was caused by increased Comptonization in the inner part of the accretion disk (Nakamura et al. 1989). Such luminosity-related spectral changes have been observed from other LMXBs (e.g., Aql X-1; see Tanaka 1994).

X1608−52 is also an X-ray burster from which several bursts with photospheric expansion have been observed (Nakamura et al. 1989). Assuming the Eddington luminosity during photospheric expansion, the distance to X1608−522 was estimated to be 3.6 kpc.

Outbursts of Cen X-4 were observed in 1969 (Conner et al. 1969; Evans et al. 1970) and 1979 (Kaluzienski et al. 1980). During the decaying phase of the latter outburst, a type-I X-ray burst was observed with Hakucho (Matsuoka et al. 1980). The most probable distance to Cen X-4 is estimated to be 1.2 kpc (Chevalier et al. 1989; McClintock, Remillard 1990). In quiescence, Cen X-4 was detected at $L_{\rm x}$ (0.5–4.5 keV) ~ 0.8–1.0×10^{33} erg s^{-1} (the Einstein Observatory) and ~ 1.5–4.2×10^{33} erg s^{-1} (EXOSAT)(van Paradijs et al. 1987). (Note that these authors assumed a distance of 2.3 kpc.) Ginga observations in 1.2–37 keV could not detect Cen X-4 in quiescence, and set an upper limit of 5×10^{32} erg s^{-1} for 1.2 kpc distance (Kulkarni et al. 1992).

In this paper we present the results of spectral analyses of X1608−52 and Cen X-4 in quiescence observed with ASCA.

2. Observations

X1608−52 was observed with ASCA from 1993 August 12, 05:50 UT through 1993 August 13, 04:00 UT. The detectors aboard ASCA comprise two solid-state imaging spectrometers (SIS) and two gas-imaging spectrometers (GIS). For more details, see Tanaka et al. (1994). The exposure time, excluding earth occultation and high background regions, was ~ 32 ks for the SIS and ~ 30 ks for the GIS. SIS data were taken in the 1CCD mode with a time resolution of 4 s. The accuracy of the time assignment of each photon in the GIS is assured to be 62.5 ms for all photons. However, in the present observation, most of the photons were time-assigned to 4 ms accuracy. Cen X-4 was observed with ASCA from 1994 February 27, 04:34 UT through 1994 February 28, 07:05 UT. The exposure time, excluding earth occultation and high-background regions, was ~ 28 ks for SIS and ~ 27 ks for GIS, respectively. SIS data were taken in the 1CCD mode with a time resolution of 4 s. The bit assignment of GIS data was changed while sacrificing the rise-time bits and part of the position and energy bits. As a result, the accuracy of the time assignment of photons is assured to be 61 μs for all photons.

3. Spectral Analysis and Results

X1608−52 and Cen X-4 were clearly detected with both the GIS and SIS. The average count rates were 0.01/0.01 count s^{-1} (GIS/SIS) and 0.02/0.03 count s^{-1} (GIS/SIS) for X1608−52 and Cen X-4. The positions of the sources deduced from the image analysis are consistent with those previously determined (Bradt, McClintock 1983) within typical errors of $1'$. No other sources were detected in the field of view.

In the analysis described below, we adopted apertures of $3'$ and $2'$ radius centered on the source position in the GIS and SIS, for selecting photons so as to maximize the quality of the spectra on the presence of background.

In order to obtain the GIS and SIS energy spectra of X1608−52 and Cen X-4, since both sources were very dim, careful background subtraction was essential. We used the superposition of high-latitude blank-sky fields as background data for Cen X-4; the data are available in a public archive. Since the galactic latitude of Cen X-4 is fairly high ($b = +23.9°$), there seems to be little contribution from emission along the galactic plane (galactic ridge emission). Actually, we found no significant difference in the background level of the GIS between the region near to the source and the blank-sky fields. In the course of background subtraction, we adjusted the cut-off rigidity ranges and the integration regions on the detectors between the on-source and background data for both the SIS and GIS in order to to compensate for the background dependence on them. It is known that SIS intrinsic background also changes with the read-out mode by about 20%. In the present observations, Cen X-4 was observed in the 1CCD mode, and the background data were accumulated in the 4CCD mode. However, we ignored this dependence, because the cosmic X-ray background, whose flux is of course independent of the read-out mode, is dominant below ~ 5 keV; also, the current data shown later have relatively good statistics only below ~ 5 keV. The energy spectra obtained are shown in figure 1.

In the case of X1608−52, we could not ignore the galactic-ridge emission, because of its low galactic latitude ($b = -0.9°$). We used background data, including the galactic-ridge emission from a neighbouring region in the same GIS field of view. However, the field of view of the SIS in the 1CCD mode is too small to obtain background data from the same field of view. We therefore used a region near to X1608−52, $(l, b) = (332.^\circ2, 0.^\circ3)$, taken during another observation as background data. For a confirmation we compared the two background data sets with the GIS data, and found no significant difference between them.

We fit the energy spectra with three conventional models: a blackbody, a thin thermal model (Raymond-Smith model), and a power-law model, respectively, with a neu-

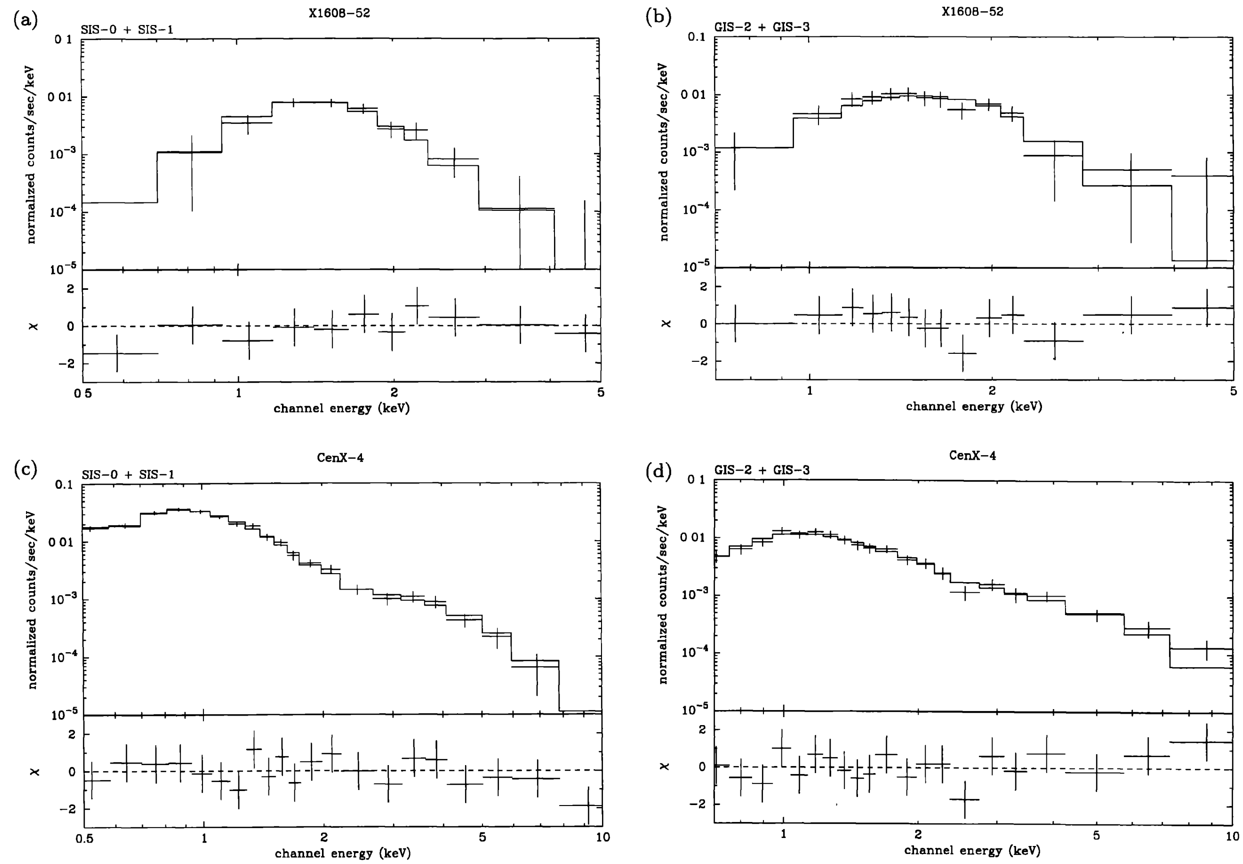

Fig. 1. Energy spectra of X1608−52 and Cen X-4 obtained with the GIS and SIS. Panels (a) and (b) show the SIS and GIS spectra of X1608−52, and panels (c) and (d) the SIS and GIS spectra of Cen X-4, respectively. The crosses represent the data points with 1 σ error bars and the histograms show the best-fit model spectrum. The model spectrum shown here is a blackbody for X1608−52 and a blackbody plus a power law for Cen X-4. Although model fitting was performed simultaneously for SIS and GIS spectra, the results are shown in a separate panel. Note that the galactic-ridge emission is subtracted from the data of X1608−52.

tral absorption column. In X1608−52, there was no significant emission above 5 keV. The counts rate was $(2\pm9)\times10^{-4}$ count s^{-1} for the GIS and $(-3.9\pm4.0)\times10^{-4}$ count s^{-1} for the SIS. The errors were at the 90% confidence limits. Therefore, we chose the energy range below 5 keV for fitting with the three models. All three models gave acceptable fits.

In Cen X-4, none of the three models gave an acceptable fit, since excess emission remained around $\sim$3–5 keV over the best-fit blackbody or thin thermal model. By making an image of $\sim$ 3–5 keV photons, we confirmed that the excess emission actually comes from Cen X-4, and is not due to an error in background subtraction. In order to investigate this residual component, we tried fitting the spectrum with the above mentioned three conventional models plus an additional power-law componente, and obtained a photon index of $\sim$ 2–3. The results are summarized in table 1. Assuming a blackbody spectrum with a neutral hydrogen column density of 1.0×10^{22} cm^{-2} and a distance of 3.6 kpc, we calculated the luminosity of X1608−52 in 0.5–10 keV. The intrinsic luminosity is 1.9×10^{33} erg s^{-1}. The intrinsic luminosity of Cen X-4 is 2.4×10^{32} erg s^{-1} , assuming a blackbody plus powerlaw spectrum and a distance of 1.2 kpc. Between 0.5 and 10 keV 54^{+16}_{-10} % of the flux is due to the blackbody component, and 46^{+10}_{-16} % to the power-law component. The radius of the blackbody emission region is estimated to be $\sim$1.5 km and $\sim$1.8 km for X1608−52 and Cen X-4, respectively.

We performed a simple periodicity search with the GIS data of X1608−52 and Cen X-4. It might be better to calculate the Fourier power spectrum in order to look for coherent pulsations using as long a dataset as possible. However, binary motion may smear out the coherent pul-

Table 1. Results of spectral fitting.*

	X1608−52	Cen X-4
Blackbody model plus a power-law		
Blackbody		
Normalization (erg cm^{-2} s^{-1})	$(1.6^{+2.4}_{-0.8}) \times 10^{-12}$	$(1.6^{+1.6}_{-0.6}) \times 10^{-12}$
kT (keV)	$0.30^{+0.07}_{-0.06}$	$0.16^{+0.03}_{-0.02}$
Power-law		
Normalization(photon s^{-1} keV^{-1} cm $^{-2}$ at 1 keV)	...	$(1.6^{+0.9}_{-0.6}) \times 10^{-4}$
Photon index	...	1.9 ± 0.3
$N_{\rm H}$ (H cm^{-2})	$(0.9 \pm 0.6) \times 10^{22}$	$< 0.2 \times 10^{22}$
χ^2_ν/d. o. f.	0.5 / 20	0.6 / 34
Thin thermal (Raymond-Smith) model plus a power-law		
Thin thermal		
Normalized emission measure (cm^{-2})	$(3^{+9}_{-1}) \times 10^{12}$	$(8^{+15}_{-3}) \times 10^{9}$
kT(keV)	$0.32^{+0.18}_{-0.08}$	0.7 ± 0.1
Power-law		
Normalization(photon s^{-1} keV^{-1} cm $^{-2}$ at 1 keV)	...	$(3.1^{+0.2}_{-0.4}) \times 10^{-4}$
Photon index	...	2.6 ± 0.1
$N_{\rm H}$ (H cm $^{-2}$)	$(2.3^{+0.6}_{-0.5}) \times 10^{22}$	$< 0.03 \times 10^{22}$
χ^2_ν/d. o. f.	0.9 / 20	1.6 / 34
Power-law model plus a power-law model		
Power-law		
Normalization (photon s^{-1} keV^{-1} cm $^{-2}$ at 1 keV)	$(7^{+25}_{-5}) \times 10^{-3}$	$(2.7^{+0.2}_{-0.7}) \times 10^{-3}$
Photon index	6^{+1}_{-2}	$7.5^{+0.8}_{-0.1}$
Power-law		
Normalization (photon s^{-1} keV^{-1} cm $^{-2}$ at 1 keV)	...	$(1.8 \pm 0.3) \times 10^{-4}$
Photon index	...	2.0†
$N_{\rm H}$ (H cm $^{-2}$)	$(1.9^{+0.1}_{-0.6}) \times 10^{22}$	$(0.73^{+0.01}_{-0.13}) \times 10^{22}$
χ^2_ν/d. o. f.	0.5 / 20	1.1 / 35

* The errors shown are in 90 % confidence limit of single parameter.
† We fixed it with the value determined by a blackbody plus a power-law fitting.

sation if the dataset is too long (Verbunt et al. 1994), and is not corrected for the orbital motion (e.g., Wood et al. 1991). The orbital period of Cen X-4, determined from optical data, is 15.1 hr (Parmar 1992). Although the orbital period of X1608−52 is not known, the typical orbital period of LMXBs may be a few hours or longer. To correct for smearing of the pulse signal we performed a single-parameter acceleration search over a grid of trial accelerations for both Cen X-4 and X1608−52. For Cen X-4, we obtained an upper limit at the 90% confidence of 50% rms amplitude using a transform length of 8192 s. For X1608−52, we also obtained an upper limit of 50% rms, which is valid if the orbital period is longer than 2 d, or if the companion mass is less than 0.01 $M_{\odot}$, using a transform of length 16384 s. In both cases the Nyquist frequency is 128 Hz. Using a transform length of 8192 s we obtained an upper limit of 70% rms in X1608−52, meaning that the source would need to be 100% modulated (modulation depth $m = 1$) to be detected at the 90% confidence level. The 50% confidence upper limit in this case is roughly 55% rms. Thus, if the orbital period of X1608−52 is between 1 and 2 days, we would, at the 50% confidence, detect coherent pulsations with an rms amplitude of 55% or larger.

4. Discussion

We detected X1608−52 and Cen X-4 at luminosity levels of order 10^{32-33} erg s^{-1}. The energy spectra are very soft, and can be approximated by a blackbody in the range below 3 keV with temperatures of $\sim$0.2–0.3 keV. These results are similar to that of the ROSAT observations of Aql X-1 in quiescence, whose spectra can also be approximated by a blackbody with a temperature of approximately 0.3 keV (Verbunt et al. 1994). Cen X-4 shows a significant hard tail with a slope of ~ 2, whereas no hard tail is seen in X1608−52.

The energy spectra of soft transients are known to become power-law at X-ray luminosities below 10^{37} down to 10^{36} erg s^{-1} (Mitsuda et al. 1989; Yoshida et al. 1993; Penninx et al. 1989 for X1608−52, and Tanaka 1994 for Aql X-1). The photon index is typically in the range 1.5–2, and is little dependent on the luminosity. There is strong evidence that the power-law spectrum is due to dominant Compton up-scattering (Nakamura et al. 1989). In contrast, the observed spectra in the present observation are much softer: power-law fits yielded photon indices of $\sim$7–8 below 5 keV for both sources. This indicates that the radiation mechanisms and/or regions change qualitatively as the luminosity goes down from 10^{36} erg s^{-1} to 10^{32-33} erg s^{-1} . With these three examples, including Aql X-1 (Verbunt et al. 1994), this change is probably a common phenomenon in the soft X-ray transients containing neutron stars.

It is unlikely that a significant fraction of the observed X-rays comes from the companion star. The companion of Cen X-4 is a normal K5–7 star (Chevalier et al. 1989; McClintock, Remillard 1990), and that of X1608−52 is most probably a late-type star, too (Grindlay, Liller 1978). The X-ray luminosities of these late-type stars are known to be $\sim 10^{30}$ erg s^{-1} or less (Dempsey et al. 1993; Güdel 1992). The intrinsic thermal emission of the neutron star, derived from its interior heat, would also be implausible. In a previous observation of Cen X-4 in quiescence by van Paradijs et al. (1987), significant flux variations were observed. Such flux variations and the small emission region, on the order of 10 km^2, obtained from the present observation, are not compatible with the thermal emission of the neutron star, itself. Therefore, the observed X-ray emission is most probably powered by mass accretion.

X-ray emissions were detected from two black-hole X-ray transients in quiescence with ROSAT: GS 2023+33 (V404 Cyg; Verbunt et al. 1994; Wagner et al. 1994; Narayan et al. 1996) and A0620−00 (McClintock et al. 1995). The energy spectrum of GS 2023+33 can be represented by either a highly absorbed soft emission (a blackbody with $kT \sim 0.21$ keV or a power law with a photon index of about 7 with an absorption of neutral gas with a column density of $N_{\rm H} = 10^{22.2}$; Wagner et al. 1994) or by a rather hard power-law spectrum with a photon index of 1.3 without extra absorption other than the interstellar absorption ($N_{\rm H} = 5 \times 10^{21}$; Narayan et al. 1996). The luminosity is estimated to be about 8×10^{33} erg s^{-1} for the former model and about 1×10^{33} erg s^{-1} for the latter model for an assumed distance of 3.5 kpc. The energy spectrum of A0620−00 is reported to be very soft. Assuming a blackbody, McClintock et al. (1995) obtained kT of about 0.16 keV and a very low luminosity at $\sim 6 \times 10^{30}$ erg s^{-1}. Both sources are low-mass binary systems, and are reliable black-hole candidates based on the optically determined mass functions (McClintock, Remillard 1986; Casares et al. 1992).

The energy spectrum of GS 2023+33 is significantly harder than the spectra of neutron-star soft transients in quiescence, although it is not clear whether the emission spectrum is intrinsically harder, or it is hard due to absorption. On the other hand, the observed blackbody temperature of A0620−00 is similar to those of the neutron-star systems. However, the luminosities of A0620−00 and soft neutron-star transients so far observed are two orders of magnitude different. Thus, the connection of quiescent emissions of black-hole and the neutron-star transients is not yet clear.

Narayan, McClintock, and Yi (1996) proposed a model for black-hole transients in quiescence based on the advection-dominant accretion-disk models (e.g., Chen et al.1995; Abramowicz et al.1995; Narayan, Yi 1995a). In the model they propose a mass-accretion rate of about 10^{15} g s^{-1}. Only less than 0.1% of the gravitational energy is emitted as radiation, because the accretion flow is optically thin inside a certain radius. The rest of the energy is brought into the black hole. In the case of a neutron-star system, however, the energy must finally be radiated, unless the neutron-star magnetic field and rotation expel the accretion flow with the "propeller effect".

The limited statistics of the present observations do not allow us to determine which emission model is most probable. In an accretion-powered neutron-star system, the accretion disk and neutron-star surface are possible sites of X-ray emission. If the emission area is optically thick, the derived area of ~ 10 km^2 for blackbody emission is too small for the disk. In fact, our calculation in the context of the standard accretion-disk model (Shakura, Sunyaev 1973) shows that the entire disk is optically thin for such a small accretion rate as 10^{13} g s^{-1} ($L_{\rm x} \sim 10^{33}$ erg s^{-1}), unless the viscosity parameter α is extremely small (Hoshi et al. in preparation). Narayan and Yi (1995b) studied the structure of accretion disks around an accreting neutron star with the framework of advection-dominant accretion-disk models. Their result also indicates that the accretion disk is entirely optically thin if the accretion rate is as small as 10^{14} g s^{-1}. If the disk is optically thin, most of the released gravitational energy will be carried onto the neutron star; hence, blackbody emission from the neutron star is expected.

If the emission region is the surface of the neutron star, the observed small blackbody area is consistent with the possibility of magnetic funneling of accreting matter to the polar-cap region. Then, a significant hard tail of Cen X-4 may be explained as either thermal emission from a shock-heated optically-thin region of the polar cap, or due to Comptonization of blackbody photons in this region or an optically-thin disk. However, the reason for the absence of a hard tail in X1608−52 at a comparable luminosity is still unclear.

Continued mass accretion onto the neutron star at a level of $\sim 10^{32-33}$ erg s^{-1} has an important implication to the rotation period and the magnetic field of the neutron stars in low-mass X-ray binaries. This has been discussed by Stella et al. (1994) and Verbunt et al. (1994). The Alfv́en radius, r_A, is given by $r_A \sim 10^8\ L_{33}^{-2/7} B_9^{4/7}$ cm, where L_{33} is the luminosity in units of 10^{33} erg s^{-1}, B_9 is the surface magnetic field in units of 10^9 G. The mass and radius of the neutron star are assumed to be 1.4 $M_\odot$ and 10^6 cm, respectively. In order for the neutron star to accrete mass, the Alfv́en radius should be smaller than the corotation radius. Otherwise, matter would be expelled by the "propeller effect" (Illarionov, Sunyaev 1975). This requires that $P \geq 0.3 L_{33}^{-3/7} B_9^{6/7}$ s, where P is the rotation period of the neutron star. The observed result, that mass accretion continues at a luminosity below 10^{33} erg s^{-1} for Cen X-4 and X1608−52, implies that the neutron stars in these systems are rotating much slower than millisecond pulsars, even if the magnetic field is as low as 10^8 G. The same conclusion holds for Aql X-1 (Verbunt et al. 1994). The failure to detect radio emission from Cen X-4 in quiescence (Kulkarni et al. 1992) is also consistent with the absence of a millisec rotator in it. Thus, it is probable that the neutron stars in these soft X-ray transients have not been spun up to millisecond rotators.

Alternatively, a situation in which the mass-accretion flow almost ceases inside a certain radius can be considered. One cause of such cases is the "propeller effect". If we assume that 10^{33} erg s^{-1} of energy is released at the Alfven radius, and that the neutron-star surface magnetic field is in the 10^{8-10} G range, the mass-accretion rate must be 10^{14-15} g s^{-1} and the Alfven radius 10^{7-8} cm. Then, the neutron-star rotation period must be shorter than 0.015–0.25 s in order to expel the accretion matter. An alternative situation can also be considered in the disk-instability models of soft transients (Mineshige, Wheeler 1989; Mineshige 1996). In these models, the accretion rate inside a certain critical radius is by many orders of magnitude smaller than that in the outer region. In extreme cases, the emission inside the critical radius can be negligibly small compared to the emission outside of it. The accretion rate in the outer region is essentially constant throughout the quiet and active states of the transient activity. Since the maximum X-ray luminosity is 10^{37-38} erg s^{-1} and the duty ratio of flare is 0.1 to 1%, the accretion rate in the outer region is $\sim 10^{15}$ g s^{-1}. Then, the optically thick disk needs be formed down to a radius of 10^8 cm in order to explain the luminosity of 10^{33} erg s^{-1}. In these cases, the X-ray emission mechanism is a problem. Up-comptonization of soft photons from the optically-thick accretion disk by a hot plasma, for example, in an accretion-disk corona may explain the X-ray emission.

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